Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 1 February 2008 (MN LaTeX style file v1.4)

The primordial baryonic clouds and their contribution to the CMB anisotropy and polarization formation.

Pavel Naselsky[1,2] and Igor Novikov[1,3,4,5]

[1] *Theoretical Astrophysics Center, Juliane Maries Vej 30, DK-2100, Copenhagen, Denmark*
[2] *Rostov State University, Zorge 5, 344090 Rostov-Don, Russia*
[3] *University Observatory, Juliane Maries Vej 30, DK-2100, Copenhagen*
[4] *Astro-Space Center of Lebedev Physical Institute, Profsoyuznaya 84/32, Moscow, Russia*
[5] *NORDITA, Blegdamsvej 17, DK-2100, Copenhagen, Denmark.*

Accepted 2001 ; Received 2001

ABSTRACT

We discuss possible distortions of the ionization history of the Universe in the model with small scale baryonic clouds. The corresponding scales of the clouds are much smaller than the typical galactic mass scales. These clouds are considered in a framework of the cosmological model with the isocurvature and adiabatic perturbations. In this model the baryonic clouds do not influence on the cosmic microwave background anisotropy formation directly as an additional sources of perturbations, but due to change of the kinetics of the hydrogen recombination . We also study the corresponding distortions of the anisotropy and polarization power spectra in connection with the launched MAP and future PLANCK missions.

Key words: cosmology: cosmic microwave background

1 INTRODUCTION.

One of the most important problems of the modern cosmology is the determination of the density and spatial distribution of the baryonic fraction of the matter.

There are several sources of information about $\Omega_b h^2 = \rho_b/\rho_{cr}$ parameter, where ρ_b and ρ_{cr} are the present values of the baryonic and critical densities and h is the Hubble constant normalized to 100 $\mathrm{km\,s^{-1}Mpc^{-1}}$. Firstly, the baryonic fraction of the matter manifests itself in the well known mass -luminosity relation for galaxies and cluster of galaxies which leads to the following value of the $\Omega_b h^2$ parameter: $\Omega_b h^2 \simeq 0.028^{+0.009}_{-0.008}$ (see for the review by Freedman et al. 2001). Another one comes from the confrontation of the Standard Big Bang Nucleosynthesis (SBBN) theory and observational data (see for the review by Fukugita, Hogan & Peebles 1998). The corresponding value of the baryonic density from this method is $\Omega_b h^2 = 0.019 \pm 0.001$. An additional empirical relation between baryonic and dark matter fractions $F_{b,m} = \Omega_b/\Omega_m \simeq 0.1$ at $h = 0.65$ comes from X-ray data on clusters of galaxies (Carlberg et al. 1996; Ettori & Fabian 1999). For the most popular ΛCDM cosmological model with $\Omega_m \simeq 0.3$ and $\Omega_\Lambda \simeq 0.7$, the corresponding value of the $\Omega_b h^2$ parameter is ~ 0.02 in agreement with the SBBN predictions.

An independent important information about the baryonic fraction of the matter in the Universe comes from the recent CMB experiments such as BOOMERANG (de Bernardis et al. 2000) and MAXIMA-1 (Hanany et al. 2000). Fitting the CMB anisotropy power spectrum to the above mentioned observational data (Tegmark & Zaldarriaga 2000; White et al. 2000 and Lesgourgues & Peloso 2000) indicates that a baryon fraction parameter should be significantly larger than the SBBN expected value, namely, $\Omega_b h^2 \simeq 0.03$. However, recently Bond & Critteden (2001) show that new BOOMERANG, MAXIMA-1 and DASI data do not contradict to $\Omega_b h^2 = 0.022 \pm 0.004$.

It is worth noting that the above mentioned methods of the baryonic fraction density estimation from the CMB and SBBN predictions are based on the simple idea that the distribution of matter (including dark matter particles and baryons) is practically homogeneous for all scales, except some fluctuations leading to the galaxy and large-scale structure formation. Typically, they are assumed to be adiabatic one. One can ask, how sensitive are the CMB data themselves to the presence of the small– scale baryonic (nonlinear) clouds before cosmological recombination and how can they transform the standard schemes of the cosmological parameter extraction from the CMB data? Definitely, this possibility is related to the isocurvature perturbations of the composite fluid which contains baryons, CDM particles, photons and neutrinos at very high redshift $z \gg 10^3$. There are a lot of modes of perturbations in the composite fluid, which is discussed by Riazuelo & Langlos (2000), Bartolo, Matarrese & Rioto (2001), Polarski & Starobinsky

(1994), Abramo & Finelli (2001), Bucher, Moodley & Turok (2000) and others. The general idea about classification of modes of perturbations is based on a very simple definition of the isocurvature modes. They do not perturb the gravitational potential. This means that the fluctuations of the total matter density ρ_{tot} are zero (see Burns 2001),

$$\delta\rho_{tot} = \sum_{i=0}^{N} \rho_i \delta_i + 4\rho_\gamma (1 + R_{\nu\gamma}) \frac{\delta T}{T} = 0, \qquad (1)$$

where ρ_i denotes the density of each massive species including baryons and different kinds of the CDM particles, $\delta_i = \delta\rho_i/\rho_i$ is the density contrast for each massive component, $R_{\nu\gamma}$ is the density ratio between neutrinos ρ_ν and black body radiation ρ_γ, and $\delta T/T$ is the CMB temperature perturbations.

We would like to point out that in the definition of the isocurvature perturbations in Eq. (1) one can find some peculiar mode (or modes) which compensates the baryonic perturbations potential, i.e., it corresponds to the condition $\rho_b\delta_b = -\rho_x\delta_x$ for some x component of the CDM particles mixture. We call below this mode as a compensate isocurvature mode (CIM) for the x-component of the dark matter particles. If several components of the dark matter particles take part in the CIM formation, we will continue to call them as x- component.⋆

In principle, for the CIM perturbations it is possible to assume that the amplitudes δ_x and δ_b are less than unity or $|\delta_x| \sim 1$ and $|\delta_b| \simeq -(\rho_x/\rho_b)|\delta_x| \gg 1$. One of the most interesting cases corresponds to the model with $\delta_x \simeq -1$, which means that some patches of the cosmological matter do not contain the CDM x-particles, but at the same patches there are non-linear clouds of the baryonic matter which compensate the perturbations of the gravitational potential. Below we will assume that a typical mass scale of the CIM perturbations is smaller than the typical galactic mass scale. This means that CIM perturbations do not influence on the CMB anisotropy formation as the additional sources of perturbations, but they can transform the kinetics of the hydrogen recombination. This leads to the transformation of the corresponding C_l power spectrum of the CMB for the adiabatic fluctuations at the scales above a few Mpc.

It is necessary to note that the idea about non-homogeneous distribution of the baryonic matter at small scales is not new. The importance of the entropic perturbations in the history of the cosmological expansion was *ad hoc* demonstrated by Doroshkevich, Zel'dovich and Novikov (1967) and Peebles (1967,1994) and recently was generalized taking into account multi-species structure of the cosmological plasma by Gnedin & Ostriker (1992), Hogan (1993) & Loeb (1993), Peebles & Juszkiewich (1998). The possible inhomogeneities of the baryon fraction distribution in the epoch of the nucleosynthesis (Inhomogeneous Big Bang Nucleosynthesis -IBBS) was widely discussed in the literature (see for the review by Jedamzik & Rehm 2001) in connection with quark-hadron phase transition. But the typical scales of such kind of peculiarities are extremely small compared to the typical mass scale $M \sim 10^5 - 10^6 M_\odot$ for the isocurvature perturbations. Other events or processes have been suggested as possible sources of the isocurvature perturbations partly connected with the baryon re-distribution in the space. For example, cosmic strings and corresponding currents and magnetic fields could generate specific features in the baryonic matter (Malaney & Butler 1989). Yokoyama & Sato (1991), Dolgov & Silk (1993), Polarsky & Starobinsky (1994), Novikov, Schmalzing & Mukhanov (2000) have shown a few different ways for the generation of the isocurvature perturbation in the framework of the inflation theory.

In connection with the above–mentioned problem of the baryonic fraction determination from the cosmological nucleosynthesis and the CMB anisotropy data we dedicate our paper to the re-examination of the models with non-linear sub-horizon-scale (at the epoch of the hydrogen recombination) baryonic clouds with $\delta_b \gg 1$. Such inhomogeneities do not manifest in the CMB anisotropy(because of the extremely small scales) but manifest themselves by the transformation of the ionization history of the primeval hydrogen-helium plasma at redshift $z \sim 10^3$. All these factors should be taken into account in the reconstruction of the ionization history of the Universe especially at the period of the cosmological hydrogen recombination . The reason for importance of the possible very small scale entropy perturbations at the epoch of recombination is connected with the very small mean free path of the Ly-α photons at $z \sim 10^3$: $l_{L\alpha} \sim 3 \times 10^{10}((1+z)/1000)^{-5/2}(\Omega_b h^2/0.02)^{-1}$ cm which corresponds to the baryon mass $M_{L\alpha} = 4\pi/3\rho_b l_{L\alpha}^3 \sim 2 \times 10^{-23}((1+z)/1000)^{-9/2}(\Omega_b h^2/0.02)^{-2} M_\odot$ where $M_\odot$ is the Solar mass. High amplitude baryonic clouds with masses $M \gg M_{L\alpha}$ could transform the process of recombination at the beginning and dissipate during recombination up to the crucial masses $M_{diss} \sim 10^5 M_\odot$ (Liu et al. 2001). We will show that if the typical masses of the clouds M are $M > M_{diss}$ the hydrogen and helium recombination inside and outside clouds goes independently. Due to non-linear dependency of the electronic ionization fraction x_e on the baryon density the hydrogen and helium inside the clouds recombine faster than outside them. Thus the dynamics of the mean value of the electronic ionization fraction x_e which plays a crucial role in the CMB anisotropy and polarization formation decreases slower than, for example, in the uniform model with the mean value of the baryonic fraction of the matter. We will show that in the cloudy baryonic plasma the kinetics of the $H - He^4$ recombination is closer to the delayed recombination model by Peebles et al. (2000) with concrete relation between ϵ_α and ϵ_i parameters of their model and amplitudes of perturbations and the filling factor of the baryonic clouds. We will show how sensitive the C_l power spectrum of the CMB anisotropy is to the mentioned above parameters of the baryonic clouds. We will discuss possible manifestation of the small scale perturbations in the MAP and upcoming PLANCK observational data.

⋆ As one can see this mode corresponds to $\delta T/T = 0$. This means that the CIM are equivalent to an isotemperature perturbations. Note, that exactly the same mode was described by Abramo & Finelli (2001), but for compensation between quintessence scalar field perturbations and some kind of the CDM-particles.

2 BASIC DEFINITIONS AND MODIFICATIONS OF THE HYDROGEN-HELIUM IONIZATION HISTORY.

We consider a model with non-linear baryonic perturbations at the small scales ($M \ll 10^{10} M_\odot$). In the analysis of the kinetics of recombination we will take into account electrons, protons, ionized and neutral hydrogen and helium. For simplicity we suppose that all baryonic clouds have the same characteristic sizes R_{cl}, which are much smaller than the size of the horizon R_{rec} close to the period of recombination ($z \sim 10^3$), $R_{cl} \ll R_{rec}$. We denote $\rho_{b,in}$, $\rho_{b,out}$ and $\rho_{b,mean}$ the baryon density inside the clouds, outside of them and the mean density at the scales much greater than R_{cl} and distances between them, respectively. We have the following relations

$$\rho_{b,mean} = \rho_{b,in} f + \rho_{b,out}(1-f), \tag{2}$$

where f is the volume fraction of the clouds. We denote

$$\xi = \frac{\rho_{b,in}}{\rho_{b,out}}. \tag{3}$$

We can write down the following relations between mean value of the baryon density and inner and outer values

$$\rho_{b,in} = \frac{\xi \rho_{b,mean}}{1+f(\xi-1)}, \tag{4}$$

and

$$\rho_{b,out} = \frac{\rho_{b,mean}}{1+f(\xi-1)}. \tag{5}$$

As mentioned in Introduction the presence of the baryonic clouds in the primordial hydrogen-helium plasma at redshift $z \sim 10^3$ changes the dynamics of the recombination due to non-linear dependence x_e on the baryon density. Below we will describe the kinetics of the recombination in a cloudy baryonic fraction of the Universe taking into account that the diffusion damping is not important for the clouds with $M > M_j$. As it was shown by Liu et al. (2001), during the period of recombination diffusion of baryons from inner to outer regions of the clouds can suppress any small scale irregularities inside the clumps. The natural length of this process is close to the Jeans length $R_J \sim c_s \eta_{rec}$ where c_s is the baryonic speed of sound and η_{rec} is the corresponding time when the plasma became transparent for the CMB radiation. Note that our aim is to predict some possible observational features in the CMB anisotropy and polarization power spectrum connected with possible non-uniform distribution of baryons on very small scales: much smaller than R_{rec}, but greater than the Jeans scale R_J. That means that for all adiabatic perturbations at the scales $M \gg 10^{13} M_\odot$ (which are the source of the Doppler peaks in the CMB anisotropy and polarization power spectra) the evolution during the period of recombination depends not on the ionization fraction inside or outside the clouds but rather on the mean value of ionization fraction over the scales of adiabatic perturbations. As we mentioned above this mean ionization fraction does not correspond to the ionization fraction for the mean value of the baryonic density due to non-linear effects. For our analysis we use two basic software packages, RECFAST (Seager et al. 2000) and CMBFAST (Seljak & Zaldarriaga 1996) with modification for the cloudy baryonic model. Let us start from CMBFAST modification because the calculation of the CMB anisotropy and polarization power spectra depends on the number density of free electrons.

For the cloudy baryonic model we introduce the mean value of the electron density

$$\langle n_e \rangle = n_{e,in} f + n_{e,out}(1-f), \tag{6}$$

where f is the fraction of volume with clouds from Eq.(2). For the baryonic clouds with scales $R > R_J$ we can neglect diffusion of baryons and $Ly-\alpha$ photons and describe the recombination process inside and outside the clouds separately. In such a case we can write down

$$\begin{aligned} n_{e,in} &= x_{e,in}\left(1-\frac{Y_{He,in}}{2}\right) n_{b,in}; \\ n_{e,out} &= x_{e,out}\left(1-\frac{Y_{He,out}}{2}\right) n_{b,out}, \end{aligned} \tag{7}$$

where $x_{e,in}$, $x_{e,out}$, $Y_{He,in}$ and $Y_{He,out}$ are the ionization fraction and helium mass fractions for inner and outer regions. Note that by definition $x_e = n_e/n_H$, where n_H is the number density of neutral and ionized hydrogen. Let us introduce the mean value of the ionization fraction $\langle x_e \rangle$,

$$\langle x_e \rangle = \frac{\langle n_e \rangle}{\langle n_b \rangle}\left(1-\frac{\langle Y_{He}\rangle}{2}\right)^{-1}, \tag{8}$$

then

$$\langle x_e \rangle = x_{e,in} G_{in} + x_{e,out} G_{out}, \tag{9}$$

where

$$\begin{aligned} G_{in} &= \frac{\xi f}{1+f(\xi-1)}\left(\frac{1-Y_{He,in}/2}{1-\langle Y_{He}\rangle/2}\right); \\ G_{out} &= \frac{1-f}{1+f(\xi-1)}\left(\frac{1-Y_{He,out}/2}{1-\langle Y_{He}\rangle/2}\right), \end{aligned} \tag{10}$$

and $\langle Y_{He} \rangle$ denotes the mean mass fraction of helium.

The second remark is related with the modification of the CMBFAST code, particularly with the characteristic time of friction τ_D between electron and radiation fluids before and at the period of the recombination. Let us consider the hydrodynamic equations for baryon-electron fluid and radiation using the Newtonian approximation . Following Liu et al. (2001), we have

$$\begin{aligned} &\dot{\rho_b} + 3H\rho_b + \nabla_i(\rho_b V_{i,b}) = 0, \\ &\qquad \dot{V_{i,b}} + HV_{i,b} + V_{j,b}(\nabla_j V_{i,b}) + \nabla_i P_b/\rho_b + \nabla_i \Psi \\ &= \frac{4\rho_\gamma a n_e \sigma_T}{3\rho_b}(V_{i,\gamma} - V_{i,b}), \end{aligned} \tag{11}$$

where $H = \dot{a}/a$, a is the scale factor of the Universe, Ψ is the gravitational potential, dot denotes the derivative with respect to time η ($d\eta = dt/a$, the speed of light $c = 1$), ρ_γ is the density of the CMB, n_e is the local concentration of electrons, $V_{i,\gamma}$ is hydrodynamic velocity of radiation (dipole moment) and σ_T is the Thompson cross-section. In our cloudy baryonic model we can define the large scale adiabatic tail of the perturbations of the matter and the small scale CIM tail as follows,

$$\begin{aligned} \rho_b &= \rho_{b,s}(\vec{r},t) + \rho_{b,l}(\vec{r},t), \\ V_{i,b} &= V_{i,b}^{(s)}(\vec{r},t) + V_{i,b}^{(l)}(\vec{r},t), \\ \Psi &= \Psi_s(\vec{r},t) + \Psi_l(\vec{r},t), \end{aligned} \tag{12}$$

where

$$\begin{aligned}
\langle\rho_b\rangle &= \langle\rho_{b,s}(\vec{r},t)\rangle + \rho_{b,l}(\vec{r},t),\\
\langle\rho_{b,s}(\vec{r},t)\rangle &= \rho_{b,mean}(t),\\
\rho_{b,l}(\vec{r},t) &= \rho_{b,mean}(t)\left(1+\delta(\vec{r},t)\right),\\
\langle V_{i,b}\rangle &= \langle V_{i,b}^{(s)}(\vec{r},t)\rangle + V_{i,b}^{(l)}(\vec{r},t),\\
\langle V_{i,b}^{(s)}(\vec{r},t)\rangle &= Hr_i,\\
\langle\Psi_l(\vec{r},t)\rangle &= \langle\Psi_s(t)\rangle + \delta\Psi_l(\vec{r},t),
\end{aligned} \tag{13}$$

and $\delta(\vec{r},t)$, $V_{i,b}^{(l)}(\vec{r},t)$ and $\delta\Psi_l(\vec{r},t)$ are the linear adiabatic perturbation of the hydrodynamic quantities. By the definition $\langle\ldots\rangle$ means average over the scales $|\vec{r}| \gg R_{cl}$ but $R_{cl}|\vec{k}| \ll 1$ for all $\vec{k}$ Fourier harmonics of the adiabatic perturbations. Using Eq. (12) and (13) we can describe the evolution of the velocity perturbations for the adiabatic modes

$$\begin{aligned}
&\frac{\partial V_{i,b}^l}{\partial\eta} + HV_{i,b}^l + \delta(\nabla_i P_{tot}/\rho_{tot}) + \nabla_i\delta\Psi_l\\
&= \Big\langle\frac{4\rho_\gamma a n_e\sigma_T}{3\rho_b}\Big\rangle(V_{i,\gamma}^l - V_{i,b}^l),
\end{aligned} \tag{14}$$

where P_{tot} and ρ_{tot} are the pressure and the density of the baryon-photon fluid and $\delta(\nabla_i P_{tot}/\rho_{tot})$ means a linear part of the perturbations. As one can see from Eq. (14) in the cloudy baryonic matter the characteristic time of baryon-radiation friction is

$$\tau_D^{-1} = \Big\langle\frac{4\rho_\gamma a n_e\sigma_T}{3\rho_b}\Big\rangle = \frac{4\rho_\gamma a\langle x_e^*\rangle\sigma_T}{3m_p}, \tag{15}$$

where m_p is the proton mass. This time τ_D depends on the local ratio $\langle x_e^*\rangle = \langle n_e(\vec{r})/n_H(\vec{r})\rangle$. The ionization fraction $\langle x_e^*\rangle$ could be written down in the following form,

$$\langle x_e^*\rangle = x_{e,in}g_{in} + x_{e,out}g_{out}, \tag{16}$$

where

$$\begin{aligned}
g_{in} &= f\left(\frac{1-Y_{He,in}/2}{1-\langle Y_{He}\rangle/2}\right);\\
g_{out} &= (1-f)\left(\frac{1-Y_{He,out}/2}{1-\langle Y_{He}\rangle/2}\right).
\end{aligned} \tag{17}$$

Thus Eq. (16) and Eq. (17) generalize the standard homogeneous model of the CMB anisotropy and polarization formation on the cloudy baryonic model of the Universe. Note the difference between Eq. (14) and the standard kinetic equation for the CMB anisotropy formation. Whereas Eq. (14) depends on $\langle x_e^*\rangle$, the standard equation depends on $\langle x_e\rangle$,(see Eq.(8) and (9)). The corresponding modification of the CMBFAST code leads to modification of RECFAST programme which calculates the kinetics of recombination inside and outside the small-scale baryonic clouds as a function of cosmological parameter $\langle\Omega_b\rangle = \rho_{b,mean}/\rho_{cr}$, density contrast ξ and volume fraction f. In Fig.1 and Fig.2 we plot the functions $x_{e,in}$, $x_{e,out}$, $\langle x_e\rangle$, and $\langle x_e^*\rangle$ for different mean values of the baryonic density $\langle\Omega_b\rangle$ and $h = 0.65$, $\xi = 11$, and $f = 0.1$. As one can see from these figures the fractions of ionization $\langle x_e\rangle$ and $\langle x_e^*\rangle$ have different shapes and different asymptotic at low redshifts.

In the next section we describe the results of the corresponding numerical computations. However, some preliminary discussions could be very useful for understanding of the most important peculiarities connected with two characteristic functions of ionization $\langle x_e\rangle$ and $\langle x_e^*\rangle$. Firstly we would like to point out that in the case when the volume fraction f is small ($f \ll 1$, but $\xi f \sim 1$!) the function $\langle x_e^*\rangle$ should be very close to $x_{e,out}g_{out}$ while $\langle x_e\rangle$ practically does not change. From Eq. (16) and Eq. (17) we can immediately find an asymptotic of the function $\langle x_e\rangle$ at low redshifts: $\langle x_e\rangle \simeq \langle x_e^*\rangle G_{out}/g_{out} = \langle x_e^*\rangle/(1+f(\xi-1)) < \langle x_e^*\rangle$. That means that the Silk damping scale which is very sensitive on the parameter τ_D^{-1}, which is proportional to $\langle x_e^*\rangle$, should increase due to the increasing of the effective ionization ratio $\langle x_e^*\rangle$. Thus we can conclude that in cloudy baryonic model the position and amplitudes of the Doppler peaks in the C_l power spectrum differ from the same values in the standard non- cloudy model with the same mean value of the baryon density $\langle\Omega_b\rangle$.

Secondly, it is well known that the so-called "visibility function" $g(\tau) = \tau^{\cdot}\exp(-\tau)$, where τ is the Thomp-

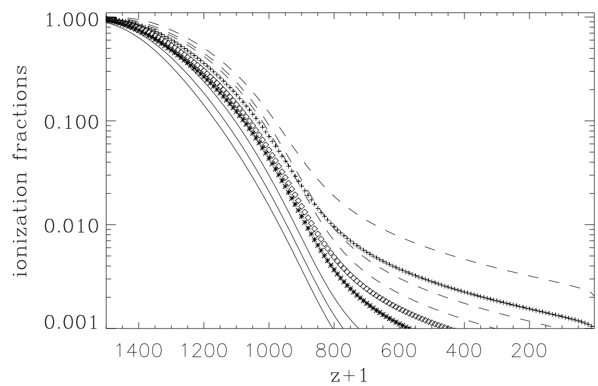

Figure 1. The fraction of ionization $\langle x_e\rangle$ as the function of z for different mean values of the baryonic density $\langle\Omega_b\rangle$ and $\xi = 11$, $f = 0.1$. From bottom to top three solid lines correspond to the fractions of ionization for inner regions of the clouds at $\langle\Omega_b\rangle h^2 = 0.03$, $\langle\Omega_b\rangle h^2 = 0.02$ and $\langle\Omega_b\rangle h^2 = 0.01$ ($h = 0.65$). Dash lines correspond to the same but for the outer regions and marked lines correspond to $\langle x_e\rangle$ for the same models.

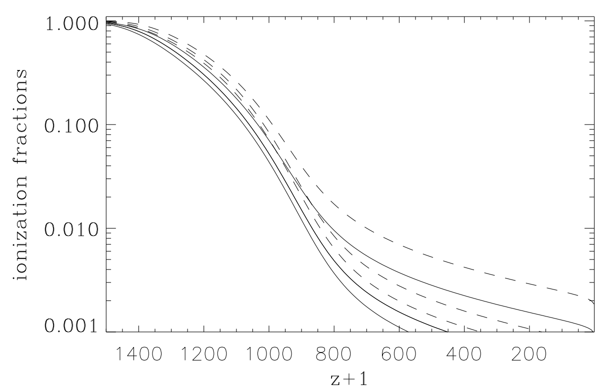

Figure 2. The fractions of ionization $\langle x_e\rangle$ and $\langle x_e^*\rangle$ as the function of z for $\xi = 11$, and $f = 0.1$. From bottom to top three solid lines correspond to the fractions of ionization $\langle x_e\rangle$ from Fig.1 for $\langle\Omega_b\rangle h^2 = 0.03$, $\langle\Omega_b\rangle h^2 = 0.02$ and $\langle\Omega_b\rangle h^2 = 0.01$ ($h = 0.65$). Dash lines from the bottom to top correspond to ionization fractions $\langle x_e^*\rangle$ at the same numeration.

son optical depth, depends on the function $\langle x_e \rangle$. Because $\langle x_e \rangle < \langle x_e^* \rangle$, and $\langle x_e^* \rangle \simeq x_{out}$ we can conclude that in our model the kinetics of recombination is similar (in general) to the models with additional sources of the ionization.

One additional comment is related with the delayed recombination model by Peebles et al. (2000) mentioned in Introduction. We would like to note, that the physical basis of their model and our cloudy baryonic model are completely different, but the numerical data for the corresponding function x_e in the model by Peebles et al. (2000) and $\langle x_e \rangle$ in our model are close to each other. If we compare the solid lines with the marked lines in Fig.1, we can conclude that change of the ionization fraction $\langle x_e \rangle$ plays a role in the corresponding delay of the recombination with respect to the recombination inside the clouds. To understand the change of the CMB anisotropy and polarization power spectra we need to compare the ionization fraction for outer regions and $\langle x_e \rangle$. From Fig.1 it is clearly seen that in such a case we can introduce the term "accelerated recombination" because the mean ionization $\langle x_e \rangle \to 0$ faster then $x_e \to 0$ for the outer regions at the same values of the $\Omega_b h^2$ parameter. In both cases, following Peebles et al. (2000), we can describe the number of additional resonance $Ly-\alpha$ quanta produced at the epoch of the hydrogen recombination by the sources of ionization

$$\frac{dn_{res}}{dt} = \varepsilon H(t) n_b, \tag{18}$$

where ε is the efficiency of the $Ly-\alpha$ quanta production, $H(t)$ is the Hubble parameter and n_b is the number density of baryons. According to Peebles et al. (2000), $\varepsilon > 0$ describes the productivity of the sources of additional resonance quanta, which leads to the delay of the hydrogen recombination. Formally, if $\varepsilon < 0$ then recombination goes faster and we have "accelerated recombination" regime. Thus, the difference between these two situations is related to the definition of the background state (inner or outer parts of the clouds). Note that for the CMB power spectrum calculations the term "accelerated recombination" is preferable because it depends mainly on the characteristics of the outer zones.

3 ANISOTROPY AND POLARIZATION POWER SPECTRA IN A CLOUDY BARYONIC UNIVERSE.

For numerical calculations of the CMB anisotropy and polarization power spectra we will use the modified CMBFAST code taking into account the above-mentioned peculiarities of the ionization history of the plasma. We take into account the difference of the He^4 mass fractions Y_{He} for inner and outer zones into account, using well estimated dependence of Y_{He} on $(\Omega_b h^2)$ parameter (Olive, Steigman & Walker 2000). For illustration of the importance of the cloudy structure at small scales on the CMB anisotropy formation in Fig.3 we plot the function $\Delta^2 T(l) = l(l+1)C_l/2\pi$ (μK^2), where C_l is the anisotropy power spectrum, for the cosmological model with $\langle \Omega_{cdm} \rangle = 0.3$, $\Omega_\lambda \simeq 0.65$, $h = 0.65$, $\langle \Omega_b \rangle h^2 = 0.02$ and $\Delta^2 T(l)$ for the corresponding model with the uniform baryonic matter distribution and scale invariant power spectrum of the initial adiabatic perturbations. We choose $f = 0.1$, and density contrast between inner and outer zones $\xi = 11$.

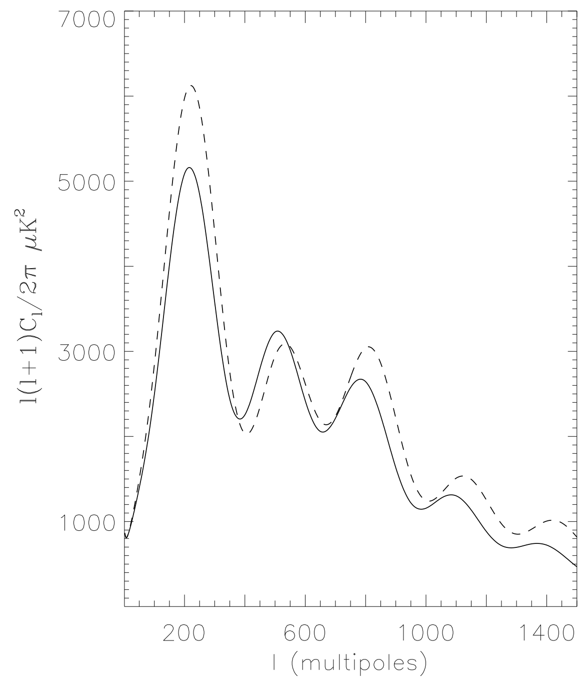

Figure 3. The $\Delta T^2(l)$ function as a function of multipole number l for $\xi = 11$, $f = 0.1$ model. The dash line corresponds to the cosmological model for $\Omega_b h^2 = 0.02$ without clouds. Solid line corresponds to the model with clouds and $\langle \Omega_b \rangle h^2 = 0.02$.

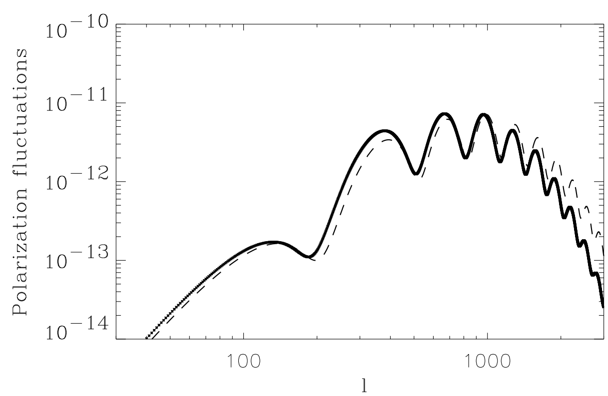

Figure 4. The polarization $\Delta^2 T_p(l) = l(l+1)C_p(l)/2\pi$ as a function of the multipole number l for $\xi = 11$, $f = 0.1$ model. The numeration of the lines is the same as in Fig.3.

As one can see from Fig.3, the presence of the clouds before and during the period of the hydrogen and helium recombination significantly perturbed the corresponding $\Delta T^2(l)$ function. The same conclusion follows from Fig.4 for the polarization of the CMB in the cloudy baryonic model.

As it is seen from Fig.4 the more complicated ionization history of the plasma in the cloudy model leads to the decreasing of the corresponding power spectrum of the polarization at $l \geq 900$ due to the increasing of the effective dissipation scale. It is worth noting that in our cloudy model we do not take into account the possible reionization of the hydrogen at low redshift $(z < 20)$ due to the influence of

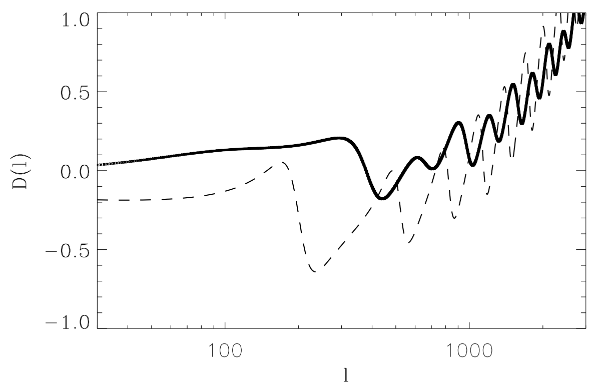

Figure 5. The functions $D(l)$ for the anisotropy (solid line) and polarization (dashed line) as functions of the multipole number l for $\xi = 11$, $f = 0.1$ model.

the additional sources on the ionization balance. This modification is the standard part of the CMB anisotropy and polarization spectrum calculations using CMBFAST codes. But it is clear that in cloudy baryonic Universe the mean value of the optical depth must be related to the mean ionization fraction $\langle x_e \rangle$ for corresponding values of the $\langle \Omega_b \rangle$ parameters.

4 CONCLUSION.

As it was mentioned in Introduction, the baryonic fraction of the matter is one of the most important cosmological parameters, which determines the most preferable model of the Universe. Two crucial parameters of the theory are now under discussion, i.e., the light chemical elements abundance, which is related directly to the SBBN predictions, and the Ω_b parameter which can be determined from the current and future CMB observations. In both cases the determination of the parameters depends on the hypothesis about the spatial distribution of the baryonic fraction of the matter and can be tested by the CMB experiments such as the launched MAP and the future PLANCK missions.

In our paper we have shown how important it is the possible baryonic inhomogeneity at small scales ($M \ll 10^{13} M_\odot$) in the CMB anisotropy and polarization formation through distortions of the cosmological recombination. The extremal case, when the density contrast $\xi \simeq 10$, shows that the clumps in the baryon fraction of the matter can significantly change the amplitudes and positions of the Doppler peaks in the CMB anisotropy and polarization power spectrum. For example in the above mentioned $\xi \simeq 10$ model the differences between C_l for the anisotropy and for the polarization in the models with $\Omega_b h^2 = 0.02$ (no clouds) and $\langle \Omega_b \rangle h^2 = 0.02$ (with clouds) are presented in Fig.5 in a form of the following the functions. For the anisotropy

$$D_a(l) = 2(C_{a,nc}(l) - C_{a,c}(l))/(C_{a,nc}(l) + C_{a,c}(l)), \qquad (19)$$

where $C_{a,nc}(l)$ and $C_{a,c}(l)$ denote the non-cloudy and cloudy model, respectively, and the index a corresponds to the anisotropy spectrum. The analogous definition of the $D_p(l)$ function is used in Fig.5 for the CMB polarization. As one can see from Fig.5, practically for all ranges of multipoles the differences between cloudy and non-cloudy models are observable for the PLANCK mission. Moreover, if the parameter $\xi \geq 1$, then we need to include the possible cloudy baryonic model in the schemes of the cosmological parameter extractions from the current and future CMB anisotropy and polarization data. As one can see from Eq.(4) and Eq.(5), if $f(\xi - 1) \ll 1$, then the difference between $\rho_{b,out}$ and mean baryon density is $\sim f(\xi - 1)$. According to the predicted accuracy of the cosmological parameter extraction from the PLANCK mission, the corresponding uncertainties for the baryonic fraction of the matter $\Delta_b = \delta\Omega_b/\Omega_b$ must be less then a few percents. Taking conservative limit $\Delta_b \simeq f(\xi - 1) \sim 0.1$ and $\xi - 1 \sim 1$ we can obtain that the corresponding fraction f should be detectable by the PLANCK satellite, if $f \geq 0.1$.

We would like to point out that our simple model of the baryonic clouds is based on the one possible modes of the isocurvature perturbations at the small scales. It would be interesting to investigate the more complicated models of the initial perturbations. This program is in progress.

ACKNOWLEDGMENTS.

Authors are grateful to A. Doroshkevich, J. Sommer-Larsen and J. Schmalzing for discussions. This paper is supported in part by Danmarks Grundforskningsfond through its support for the establishment of the Theoretical Astrophysics Center, by grants RFBR 17625 and INTAS 97-1192.

REFERENCES

Abramo, L. R. & Finelli, F., 2001, Phys. Rev. D, 64 , 083513
Bartolo, N., Matarrese, S. & Rioto, A., 2001, Phys. Rev. D., 64, 123504
Bucher, M., Moodley, K. & Turok, N., 2000, preprint(astro-ph/0012141)
Carlberg, R.J., Yee, H.K.C.,Ellingson, E., Abraham, R., Gravel, P., Morris, S. & Pritchet, C.J., 1996, ApJ, 462, 32
de Bernardis, P., et al. 2000, Nature, 404, 955
Dolgov, A. & Silk, J., 1993, Phys. Rev. D, 47, 2619
Doroshkevich,A. G., Zeldovich Ya. B.,& Novikov, I. D., 1967, Sov.Astron., 11, 233
Ettori, S. & Fabian, A.C., 2000, MNRAS, 317, L57
Gnedin ,N. Iu. & Ostriker, J. P., 1992, ApJ, 400, 1
Hanany, S., et al., 2000, ApJ, 545, L5.
Hogan, C. J., 1993, ApJ, 415, 63
Jedamzik, K. & Rehm, J.B., 2001, Phys. Rev. D, 64, 023510
Freedman , W.L. et al., 2001, ApJ, 553, 47
Fukugita, M., Hogan, C.J. & Peebles, P.J.E., 1998, ApJ, 503, 518
Lesgourgues, J. & Peloso, M., 2000, Phys. Rev. D, 62, 081301
Yokoyama, J. & Sato, Y., 1991, ApJ, 379, 427
Liu, G.-C., Yamamoto, K., Sygiyama, N. & Nishioka, H., 2001, ApJ, 547, 1
Loeb, A., 1993, ApJ, 404, 37
Malaney, R.A. & Butler, M.N., 1989, Phys. Rev. Lett., 62, 117
Novikov, D.I., Schmalzing, J. & Mukhanov, V.F., 2000, A&A, 364, 17
Olive, K. A., Steigman G. & Walker,T. P., 2000, ApJ, 333, 389
Peebles, P.J.E., 1967, ApJ, 147, 859
Peebles, P.J.E., 1994, ApJ, 432, 5
Peebles, P.J.E. & Juszkiewicz, R., 1998, ApJ, 509, 483
Peebles, P.J.E., Seager, S. & Hu, W., 2000, ApJ, 539, L1

Polarski, D. & Starobinsky, A., 1994, Phys. Rev. D, 50, 6123
Riazuelo, A. & Langlos, D., 2000, Phys. Rev. D 62, 043504
Seager, S., Sasselov, D.D. & Scott, D., 2000, ApJS, 128, 407
Seljak,U. & Zaldarriaga, M., 1996, ApJ, 469, 437
Tegmark, M. & Zaldarriaga, M., 2000, Phys. Rev. Lett., 85, 2240
White, M., Scott, D. & Pierpaoli, E., 2000, ApJ, 545 , 1